Europa Clipper Thermal Control Valve Thermal and Hydraulic Analysis and Development Testing

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Europa Clipper MPFL

- Europa Clipper is a solar powered spacecraft that will orbit Jupiter and flyby Europa
  - Spacecraft has to be designed to operate exposed to 50-3200 W/m^2 solar irradiance
  - It is power constrained due to the weak solar irradiance at 5.6 AU and severe radiation environment

- Clipper thermal subsystem has designed a dual purpose single-phase mechanically pumped fluid loop for the mission to
  - Reject excess heat during Venus and earth flybys
  - Harvest heat from the electronic boxes and utilize it to maintain propulsion component temperatures above their allowable limits during Jupiter orbit

- HRS needs to modulate heat loss from the radiator surface between 350 W and 10 W at 0.65 AU and 5.6 AU by utilizing
  - Passive thermal control valves to bypass the radiator in cold environments
  - Low temperature louvers mounted on the radiator to minimize heat loss from the spacecraft while protecting working fluid from freezing

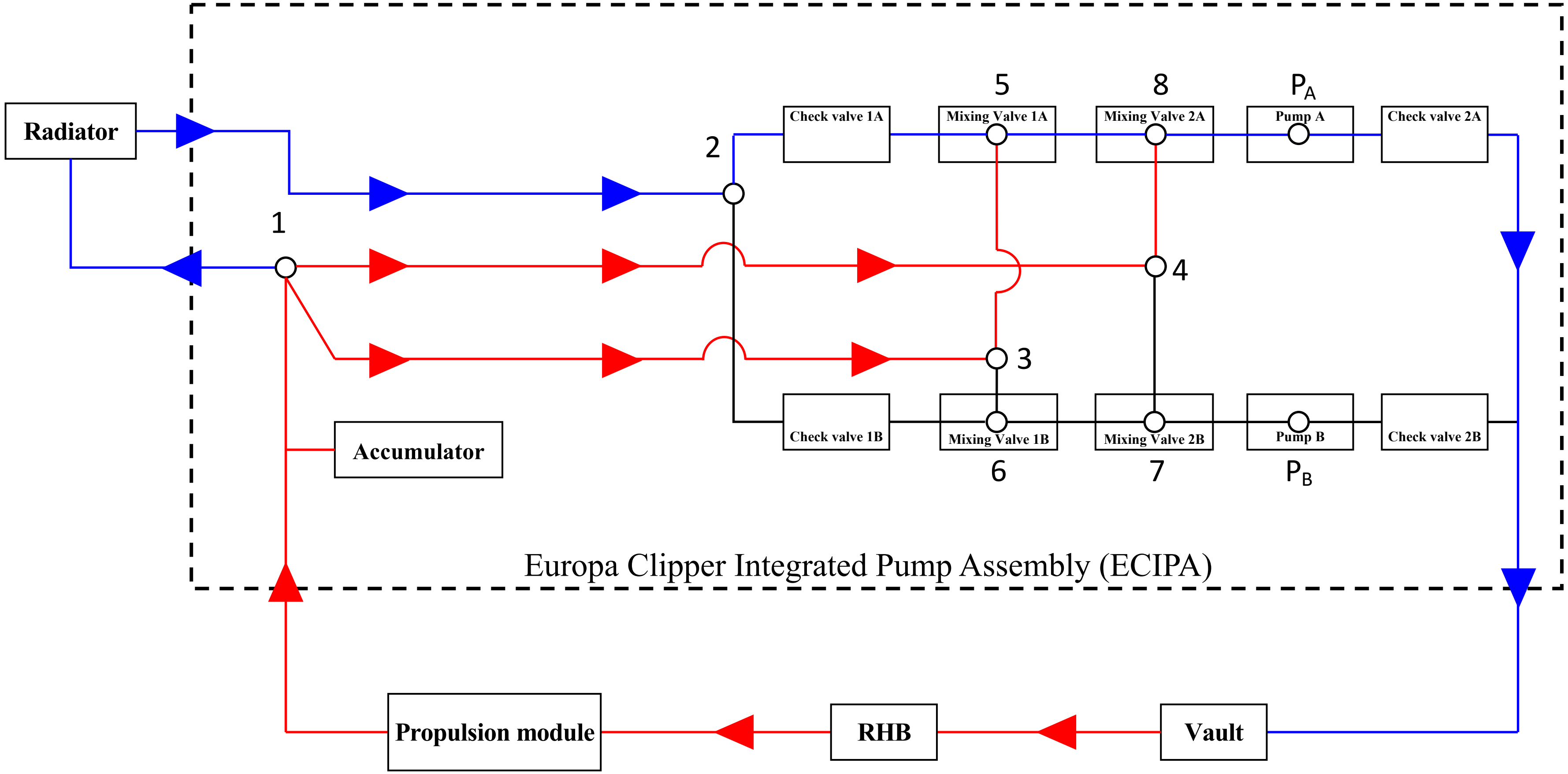
Objective of this study

- For the first time Clipper is using two Mars mission heritage thermal control valves (TCV) in series to reduce flow rate to the radiator to <0.3%
  - Each TCV has a flow rate ranging from 4% to 96% over a temperature range of 20 ^{o}C
  - The radiator circuit in series with the thermal control valves also adds impedance to the system affecting the flow split between the radiator and the bypass
- Block redundancy in the thermal control valve may create parasitic flow paths and recirculation that may reduce the flow rate to the radiator in hot conditions negatively affecting spacecraft temperatures

- Objectives of the study:

1. Thermal and hydraulic analysis were performed to
   a) Determine flow rate to the radiator as a function of fluid temperature of the mixing valves
   b) Determine leak paths between the block redundant pairs of the thermal control valves
2. Each TCV contains silicone oil actuator and a test was performed to determine if ionizing radiation altered device characteristics

Simplified fluid loop diagram



TCV: thermal control valve
RHB: replacement heater block

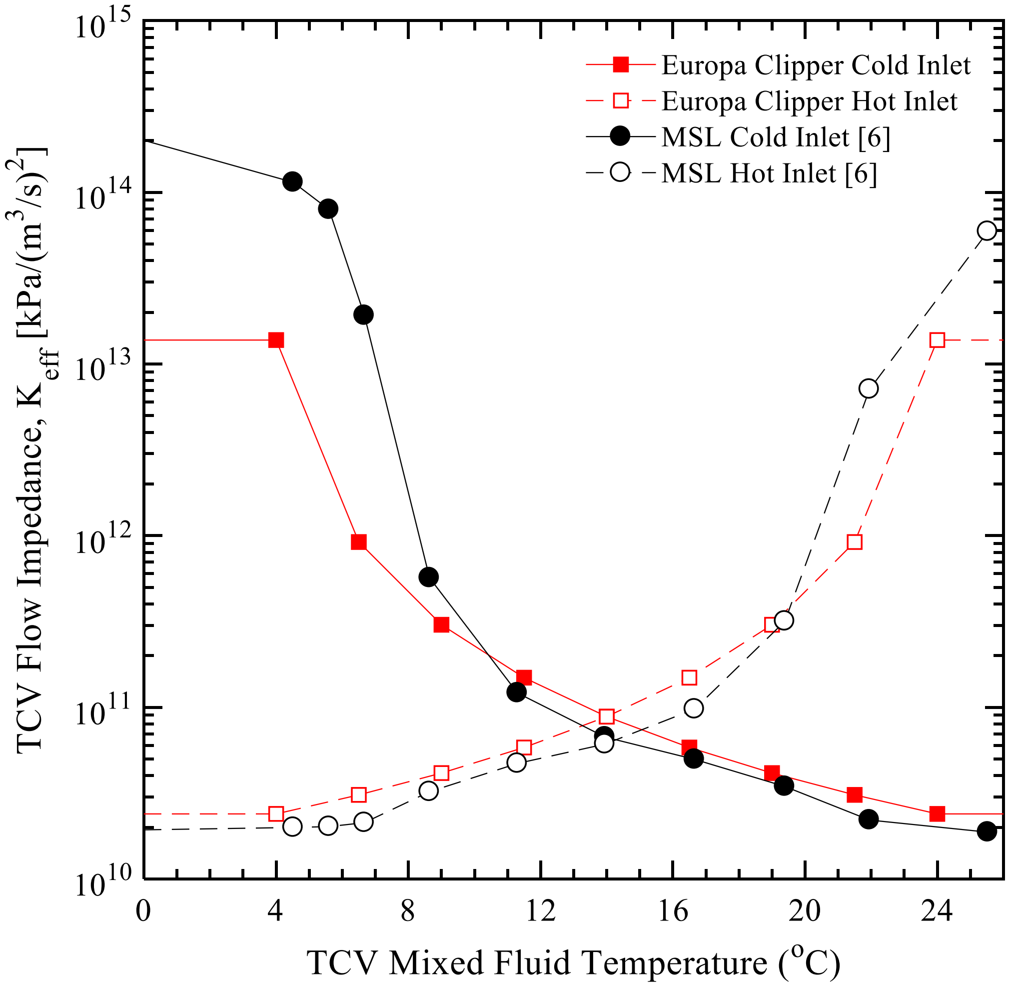
Note: Loop components not relevant to the current such as filters and pressure transducers study omitted from diagram

The approach to hydraulic analysis

- The impedance of the check valve, RHB, PM, Vault, and radiator were estimated based on vendor data or analysis presented by Bhandari et al. (ICES 2018)

- Pressure drop estimated based on the following equations
  - $\Delta P = \frac{1}{2}\rho\left(\frac{fL}{D}\right)v^2 = \frac{1}{2}\rho K v^2$
  - $f = \frac{64}{Re}$ laminar, $f = 0.18Re^{-0.2}$ turbulent
  - $\Delta P = \frac{1}{2}\rho K\frac{\dot{V}^2}{A^2} = K_{eff}\dot{V}^2$

- Thermal control valve temperature dependent impedance was estimated based on requirements imposed on the vendor
  - Comparison to MSL test data suggests the unit tested exceeded the performance requirements
  - Requirement is 13.8 kPa ΔP between inlet and outlet at any flow rate and min/max flow rate of 0.06 to 1.5 LPM from each inlet port



[6] G. C. Birur et. al., 38th International Conference On Environmental Systems , San Francisco, CA, 2008.

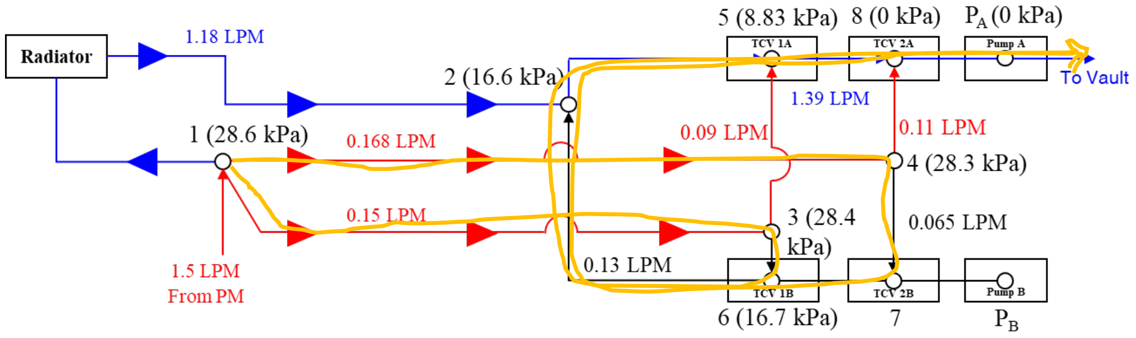
WCH conditions

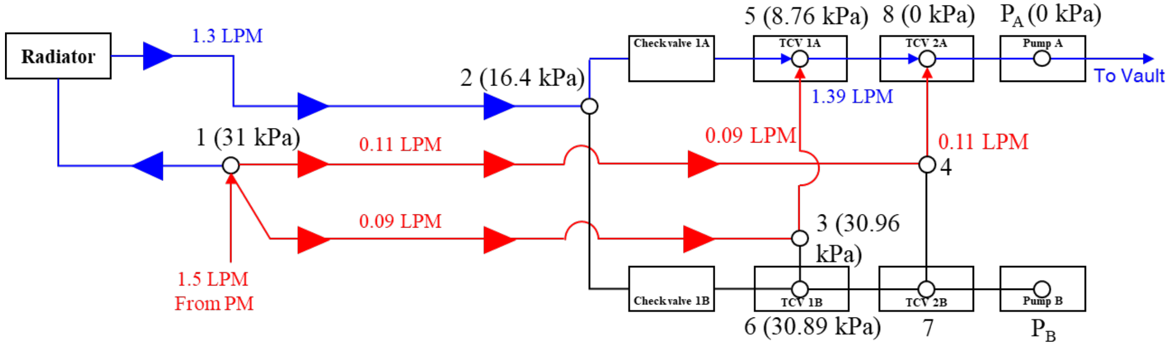
- With no check valves upstream of TCV 1 radiator in WCH conditions is 1.18 LPM
  - 10% of flow goes into recirculation between the redundant TCVs
  - Nodes 3 and 4 are high pressure compared to 2 and will drive flow from 1→4→2 and 1→3→2 bypassing the radiator
  - Estimated impact on spacecraft is 2-3 °C increase in temperatures

- Radiator and check valve flow impedances limit the maximum flow to the radiator to 1.3 LPM (87% of full flow rate of 1.5 LPM) compared to 1.38 LPM (92.1% of full flow rate) if the radiator and check valve impedance were negligible

- Each check valve constitutes 4% of overall system pressure drop and eliminating this component would increase system flow rate

Assume fluid temperature at the inlet of the pump is > 24 °C

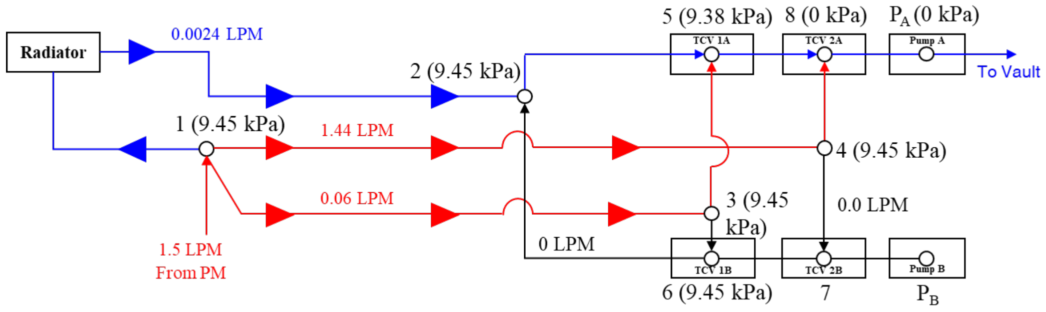


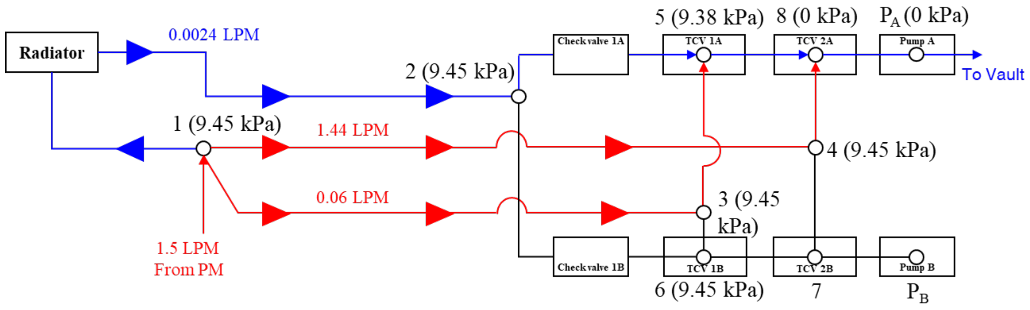


WCC conditions

- Check valves upstream of TCV 1 had no impact in the WCC conditions as nodes 1, 2, 3, and 4 were all at equal pressure and therefore no recirculation was present between node 3 or node 4 and node 2
- Check valves do not add significant pressure drop to the system in the cold case because there is no significant flow through them
- Bypassing the 23 m long radiator circuit reduces overall system impedance by 15 %

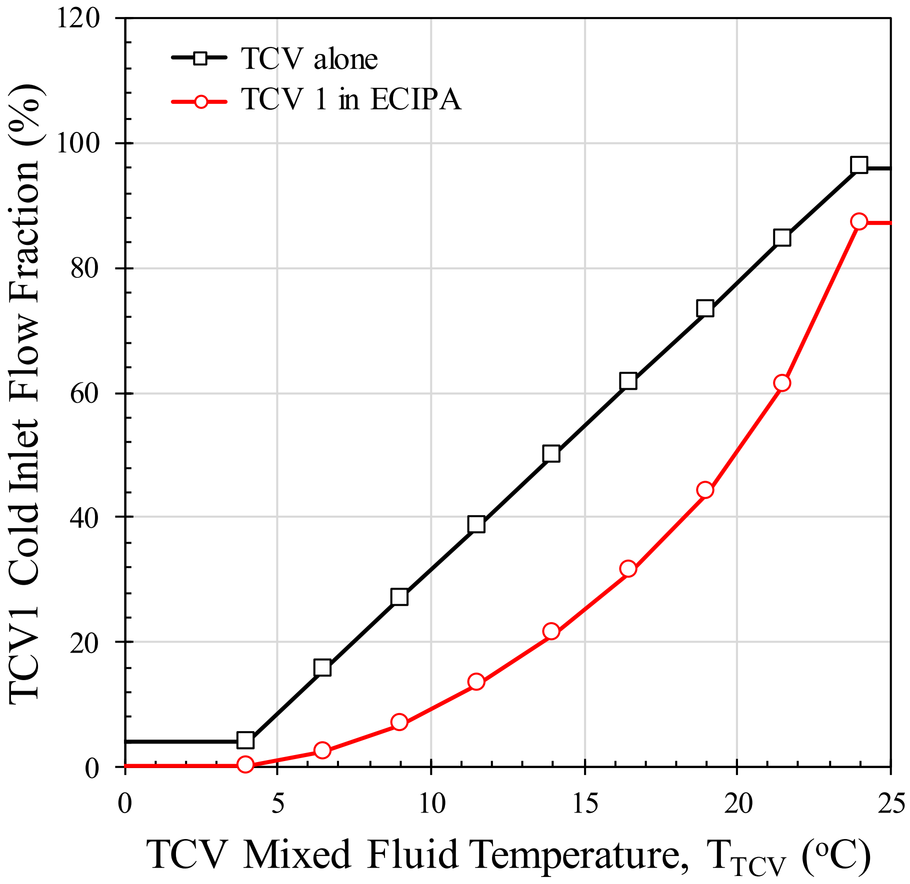
Assume fluid temperature at the inlet of the pump is < 4 °C





Full temperature range

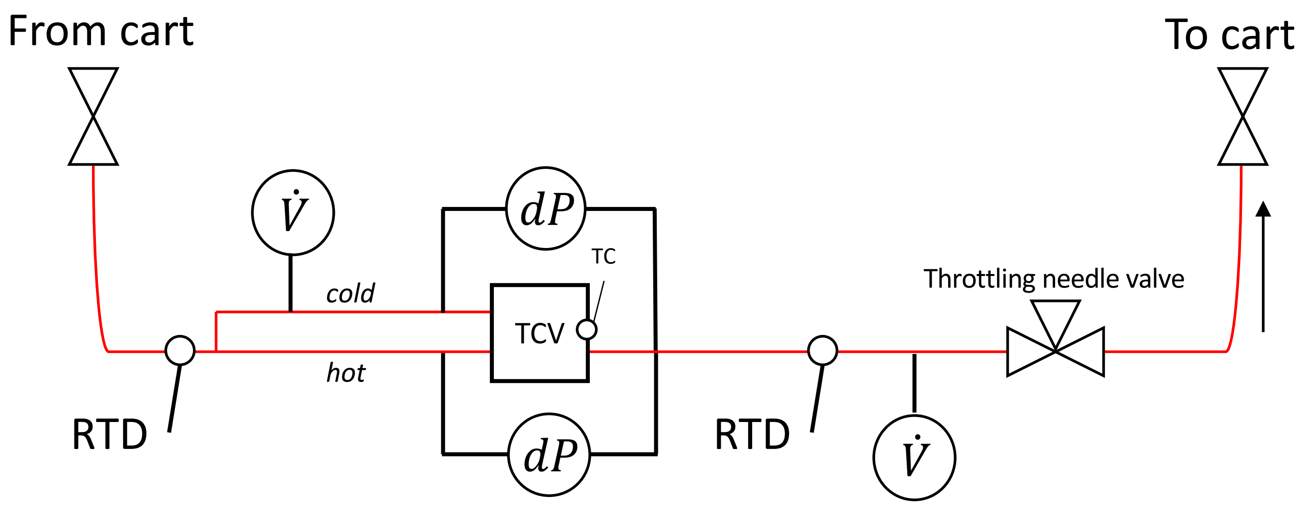
- Minimum flow rate that can be achieved by a single TCV is 4% at the cold set point of 4 °C while it is 0.16% for two TCVs in series
- Maximum flow rate from the cold inlet of an individual TCV is 96% at the hot set point of 24 °C while it is 87% for two TCVs in series
  - The impedance from the radiator circuit is significant and affects maximum flow rate in a fully open valve
  - Placing orifices in the bypasses to match the impedance of the radiator may help mitigate this effect but it introduces higher flow rate through the radiator in the cold case resulting in undesirably higher heat loss
- Individual TCV cold inlet flow rate increased linearly between 4 - 24 °C while two TCVs in series featured a parabolic increase in flow rate to the radiator vs temperature
  - Temperature of loop components will be slightly warmer with two TCVs in series
  - This trade was favored due to significantly lower flow rate to the radiator and smaller heat loss from the spacecraft in the cold case



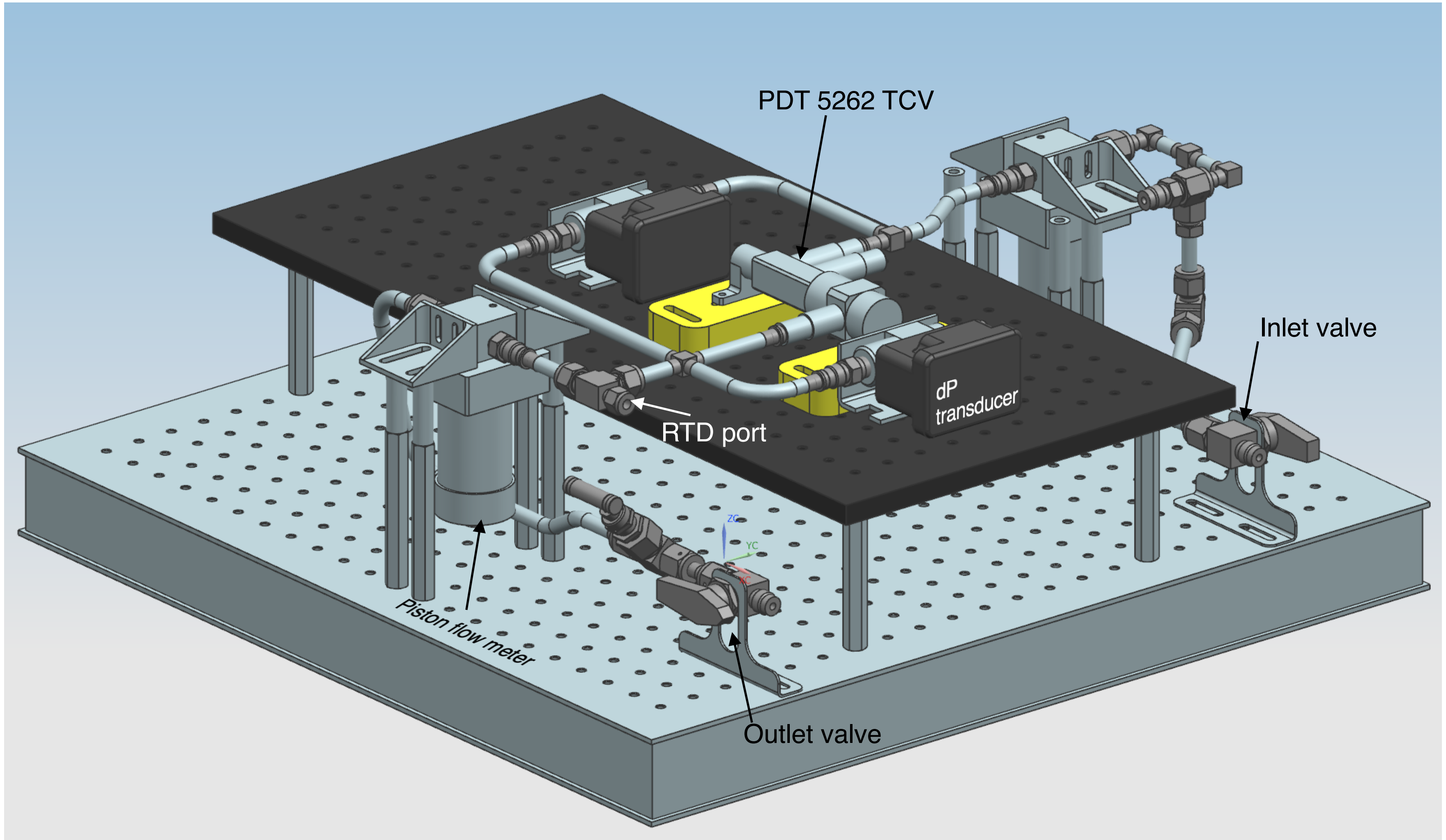
Test setup

- Test setup to perform flow rate vs temperature measurement before and after radiation
- The test section was connected to a pre-existing flow cart
  - Flow cart has a fluid and vacuum pumps, accumulator, cooler, heater, and a PID temperature controller

- FC-72 fluorinert used as working fluid: Europa Clipper working fluid is CFC-11 but FC-72 has similar density and viscosity and is non-hazardous

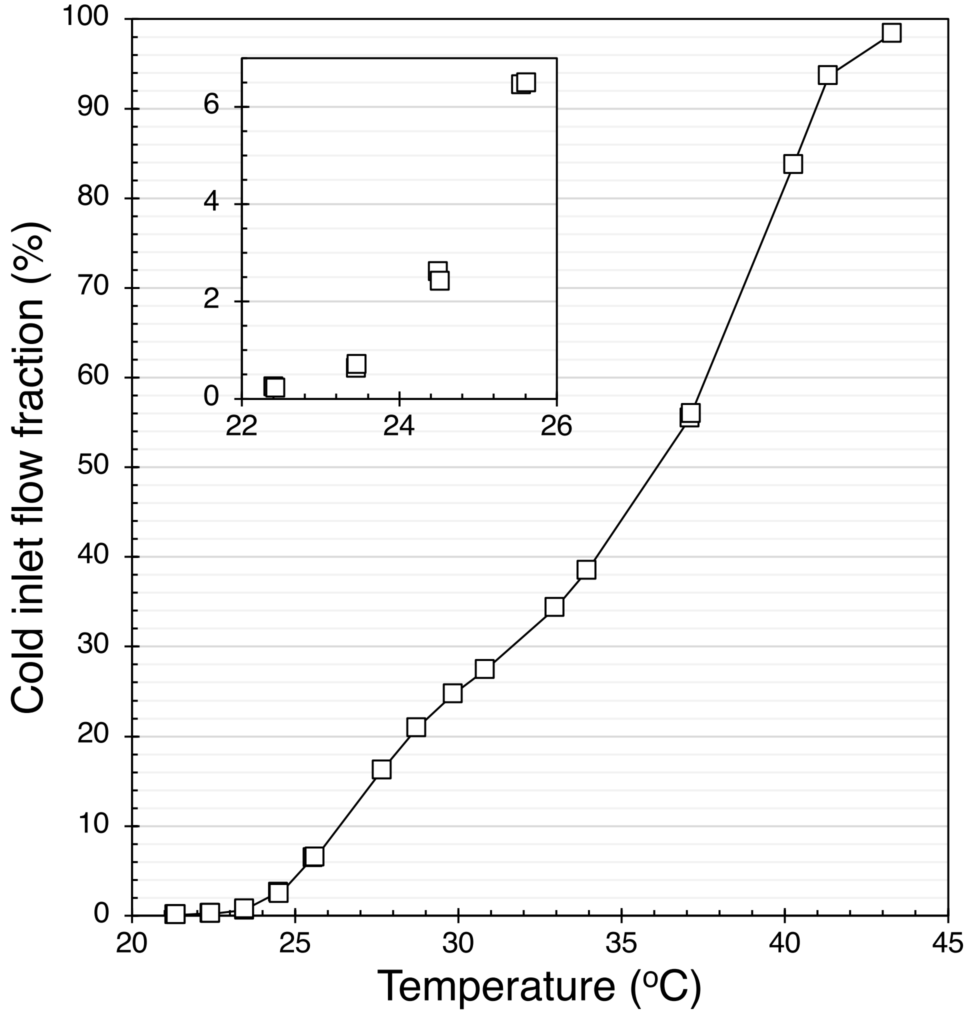


Test setup


PDT 5262 TCV
Inlet valve
dP
transducer
RTD port
Piston flow meter
Outlet valve

Test Results

- The actual set points of the valve were 22-42 °C
- The curve was repeated 22-26 °C to verify the results before radiation testing
  - The two measured values were within 15%
- The minimum and maximum flow rates of the cold inlet were 0.07% and 99.2% respectively
- For the most part cold inlet flow fraction vs temperature was linear
- No hysteresis was observed
  - The flow fraction was the same whether temperature was increasing or decreasing

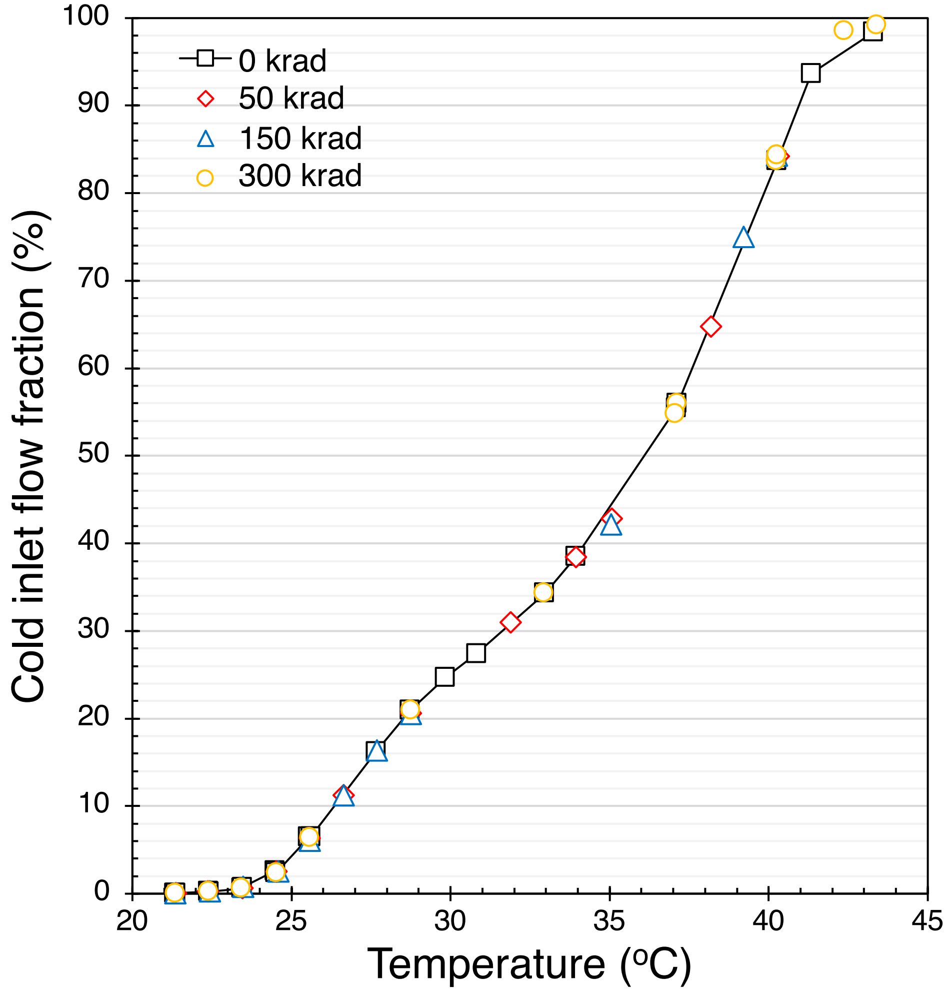


Effects of radiation

- No changes in valve inlet flow rate observed as a function of TID for all temperatures
  - Analysis suggests 1% change in density (due to radiation) would results in a large (>5 ^oC) change in setpoint

- Test setup limited the fluid temperature to below 42 ^oC

- Could not measure flow rate <21 ^oC as it fell out of the flowmeter specs



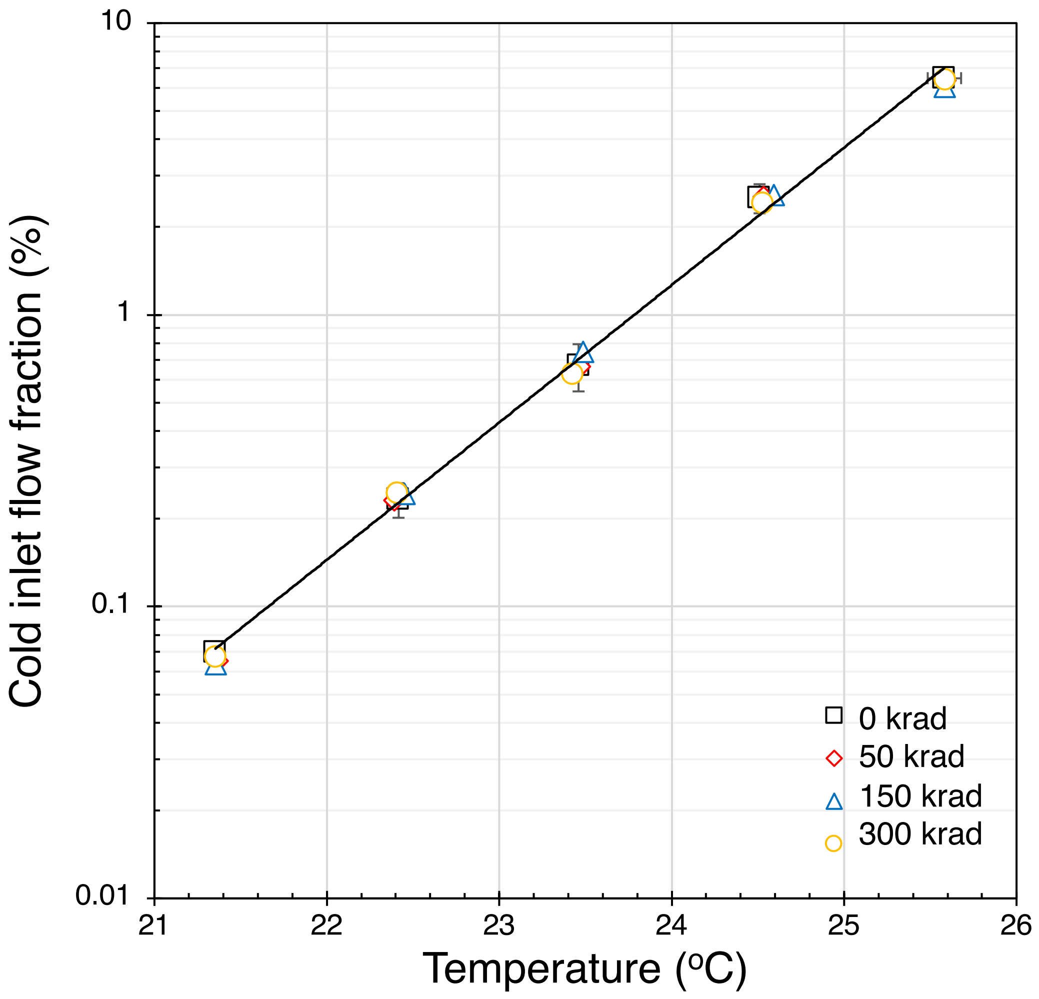
Around the set point (Zoomed in view)

- No change in cold inlet flow rate observed when the valve was radiated to 300 krad

- For example at 21.4 ^{o}C pre radiation leak rate was 0.07% and 0.065%, 0.063%, 0.067% after 50, 150, and 300 krad exposure

- Error bars correspond to 95% confidence interval (n=2)

- The line is an exponential curve fit of the pre-radiation data (note the log scale y-axis)



Summary

- Thermal and hydraulic analysis
  - Parasitic flow paths were discovered through the block redundant pairs of TCVs and check valves were used to mitigate it
  - Two TCVs in series was shown to minimize flow rate to the radiator to 0.16% at mixed fluid temperatures of <4 ^{o}C
  - At mixed fluid temperature >24 ^{o}C the maximum flow to the radiator was 87% this was less than 92% that could be achieved without flow impedance from the radiator
  - Two TCVs in series feature a parabolic increase in flow rate to the radiator as a function of TCV mixed fluid temperature

- Radiation test
  - Heritage thermal control valve was exposed to up to 300 krad of TID in the high dose chamber
  - Flow rate in each port was measured before and after radiation exposure
  - No changes were measured in valve characteristics due to radiation exposure

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